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A DYNAMICAL LEFT–RIGHT SYMMETRY BREAKING MODEL *

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ABSTRACT

Left–right symmetry breaking in a model with composite Higgs scalars is discussed. It is assumed that the low–energy degrees of freedom are just fermions and gauge bosons and that the Higgs bosons are generated dynamically through a set of gauge– and parity–invariant 4-fermion operators. It is shown that in a model with composite bi-doublet and two triplet scalars there is no parity breaking at low energies, whereas in the model with two doublets instead of two triplets parity is broken automatically regardless of the choice of the parameters of the model. For phenomenologically allowed values of the right–handed scale the tumbling symmetry breaking mechanism is realized in which parity breaking at a high scale μ_R propagates down and eventually causes the electroweak symmetry breaking at the scale $\mu_{EW} \sim 100$ GeV. The model exhibits a number of low and intermediate mass Higgs bosons with certain relations between their masses. In particular, the $SU(2)_L$ Higgs doublet χ_L is a pseudo–Goldstone boson of the accidental (approximate) $SU(4)$ symmetry of the Higgs potential and therefore is expected to be relatively light.

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Several years ago, a very interesting approach to electroweak symmetry breaking was put forward, so called "top condensate" model[1)–4)]. In this model no fundamental Higgs boson is present; instead, it is assumed that there is a strong attractive interaction between the top quarks, which can lead to the formation of the $t\bar{t}$ bound state playing a role of the Higgs scalar. This interaction is assumed to result from a new physics at some high–energy scale Λ, the origin and precise nature of which are not specified. At low energies this new physics would manifest itself through non-renormalizable interactions between usual fermions and gauge bosons. At the energies $E \ll \Lambda$ the lowest dimensional operators are most important, which are just the four–fermion (4-f) operators. The simplest gauge–invariant 4-f operator which includes the heaviest top quark is

$$\mathcal{L}_{4f} = G(\bar{Q}_{Li}t_R)(\bar{t}_R Q_{Li})\,, \tag{1}$$

where Q_L is the left–handed doublet of third generation quarks, G is the dimensionful coupling constant, $G \sim \Lambda^{-2}$, and it is implied that the colour indices are summed over within each bracket. This 4-f interaction can be studied analytically in the large N_c (number of colours) limit in the fermion bubble approximation. For large enough G ($G > G_{cr} = 8\pi^2/N_c\Lambda^2$) the electroweak symmetry gets spontaneously broken, $W^\pm$ and Z^0 bosons and top quark acquire masses, and a composite Higgs scalar doublet $H \sim \bar{t}_R Q_L$ is formed.

The top condensate approach reproduced correctly the structure of the low–energy effective Lagrangian of the standard model and demonstrated how the electroweak symmetry breaking can result from a high–energy dynamics. The question naturally arises as to whether a similar approach can work in more complicated cases, i.e. whether the Higgs sectors and symmetry breaking patterns of more complicated models can always be successfully described starting from a set of gauge–invariant 4-f operators. In this talk I will report the main results of the analysis of dynamical symmetry breaking in the left–right symmetric models done in collaboration with M. Lindner, E. Schnapka and J.W.F. Valle[5)].

We studied dynamical symmetry breaking in the left–right symmetric (LR) models based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ following the BHL approach to the standard model [3)]. The Higgs sector of the most popular LR model consists of a bi-doublet $\phi \sim (2,2,0)$ and two triplets, $\Delta_L \sim (3,1,2)$ and $\Delta_R \sim (1,3,2)$. Assuming that these scalars are composite, their fermionic content is

$$\phi_{ij} \sim \alpha(\bar{Q}_{Rj}Q_{Li}) + \beta(\tau_2\bar{Q}_L Q_R\tau_2)_{ij} + \text{leptonic terms}\,,$$

$$\vec{\Delta}_L \sim (\Psi_L^T C\tau_2\vec{\tau}\Psi_L), \;\; \vec{\Delta}_R \sim (\Psi_R^T C\tau_2\vec{\tau}\Psi_R)\,. \tag{2}$$

Here Q_L, Ψ_L (Q_R, Ψ_R) are left–handed (right–handed) doublets of quarks and leptons, respectively; i and j are isospin indices.

In models with Higgs bosons generated by 4-f operators the composite scalars are, roughly speaking, "square roots" of these 4-f operators. One can therefore obtain the above composite Higgs bosons starting from the 4-f operators which are "squares" of the expressions in eq. (2). A convenient way to study models with composite Higgs bosons is the auxiliary field technique, in which one introduces the static auxiliary scalar fields (with appropriate quantum numbers)

with Yukawa couplings and mass terms but no kinetic terms and no quartic couplings. One can use the equations of motion for these fields to express them in terms of the fermionic degrees of freedom and recover the initial 4-f structures.

The static auxiliary fields can acquire gauge invariant kinetic terms and quartic self–interactions through the radiative corrections and become physical propagating scalar fields at low energies provided that the corresponding gap equations are satisfied[3)]. The kinetic terms and mass corrections can be derived from the 2–point Green function, whereas the quartic couplings are given by the 4–point functions. Given the Yukawa couplings of the scalar fields, one can readily calculate these functions in the fermion bubble approximation, in which they are given by the corresponding 1-fermion–loop diagrams.

It is usually assumed that the Higgs potential of the LR model is exactly symmetric with respect to the discrete parity symmetry. However, parity can be spontaneously broken by $\langle\Delta_R\rangle > \langle\Delta_L\rangle$ provided $\lambda_2 > \lambda_1$ where λ_1 and λ_2 are the coefficients of the $[(\Delta_L^\dagger\Delta_L)^2+(\Delta_R^\dagger\Delta_R)^2]$ and $2(\Delta_L^\dagger\Delta_L)(\Delta_R^\dagger\Delta_R)$ quartic couplings in the Higgs potential. In the conventional approach, λ_1 and λ_2 are free parameters and one can always choose $\lambda_2 > \lambda_1$. On the contrary, in the composite Higgs approach based on a certain set of the effective 4-f couplings, the parameters of the effective Higgs potential are not arbitrary: they are all calculable in terms of the 4-f couplings G_a and the scale of new physics Λ [3)]. In particular, in the fermion bubble approximation at one loop level the quartic couplings λ_1 and λ_2 are induced through the Majorana–like Yukawa couplings $f(\Psi_L^T C\tau_2\vec{\tau}\vec{\Delta}_L\Psi_L + \Psi_R^T C\tau_2\vec{\tau}\vec{\Delta}_R\Psi_R) + h.c.$.

It is easy to see that to induce the λ_2 term one needs the Ψ_L–Ψ_R mixing in the fermion line in the loop, i.e. the lepton Dirac mass term insertions. However, the Dirac mass terms are generated by the VEVs of the bi-doublet ϕ; they are absent at the parity breaking scale which is supposed to be higher than the electroweak scale. Even if parity and electroweak symmetry are broken simultaneously (which is hardly a phenomenologically viable scenario), this would not save the situation since λ_2 is finite in the limit $\Lambda \to \infty$ whereas the diagrams contributing to λ_1 are logarithmically divergent and so the inequality $\lambda_2 > \lambda_1$ cannot be satisfied.

One is therefore led to consider a model with a different composite Higgs content. The simplest LR model includes two doublets, $\chi_L \sim (2, 1, -1)$ and $\chi_R \sim (1, 2, -1)$, instead of the triplets Δ_L and Δ_R. As we shall see, the model with composite doublets will automatically lead to the correct pattern of the dynamical breaking of parity. In conventional LR models, one can have the doublet Higgs bosons without introducing any other new particles. In our model all scalars are composite, thus we must introduce additional singlet fermions – otherwise it would not be possible to build up the composite χ_L and χ_R fields. We assume that in addition to the usual quark and lepton doublets there is a gauge–singlet fermion $S_L \sim (1,\ 1,\ 0)$. To maintain the discrete parity symmetry one needs a right–handed counterpart of S_L. This can be either another particle, S_R, or the right–handed antiparticle of S_L, $(S_L)^c \equiv C\bar{S}_L^T = S_R^c$. The latter choice is more economical and, as we shall see, leads to the desired symmetry breaking pattern. We therefore assume that under parity operation $S_L \leftrightarrow S_R^c$. With this new singlet and usual

quark and lepton doublets one can introduce the following gauge–invariant 4-f interactions[5]:

$$
\begin{aligned}
\mathcal{L}'_{4f} \;=\;& G_1(\bar{Q}_{Li}Q_{Rj})(\bar{Q}_{Rj}Q_{Li}) + [G_2(\bar{Q}_{Li}Q_{Rj})(\tau_2\bar{Q}_L Q_R\tau_2)_{ij} + h.c.] \\
& + G_3(\bar{\Psi}_{Li}\Psi_{Rj})(\bar{\Psi}_{Rj}\Psi_{Li}) + [G_4(\bar{\Psi}_{Li}\Psi_{Rj})(\tau_2\bar{\Psi}_L\Psi_R\tau_2)_{ij} + h.c.] \\
& + [G_5(\bar{Q}_{Li}Q_{Rj})(\bar{\Psi}_{Rj}\Psi_{Li}) + h.c.] + [G_6(\bar{Q}_{Li}Q_{Rj})(\tau_2\bar{\Psi}_L\Psi_R\tau_2)_{ij} + h.c.] \\
& + G_7[(S_L^T C\Psi_L)(\bar{\Psi}_L C\bar{S}_L^T) + (\bar{S}_L\Psi_R)(\bar{\Psi}_R S_L)] + G_8(S_L^T C S_L)(\bar{S}_L C\bar{S}_L^T)\,. \qquad (3)
\end{aligned}
$$

These interactions are not only gauge invariant, but also (for hermitean G_2, G_4, G_5 and G_6) symmetric with respect to the discrete parity symmetry.

The composite Higgs scalars which can be induced by these 4-f couplings include, in addition to the bi-doublet ϕ of the structure given in eq. (2), two doublets χ_L and χ_R and also a singlet σ:

$$
\chi_L \sim S_L^T C\Psi_L, \quad \chi_R \sim \bar{S}_L\Psi_R = (S_R^c)^T C\Psi_R, \quad \sigma \sim \bar{S}_L C\bar{S}_L^T. \qquad (4)
$$

Under parity $\chi_L \leftrightarrow \chi_R$, $\sigma \leftrightarrow \sigma^\dagger$.

In the auxiliary field formalism the scalars χ_L, χ_R, ϕ and σ have the following bare mass terms and Yukawa couplings:

$$
\begin{aligned}
\mathcal{L}_{aux} \;=\;& -M_0^2(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R) - M_1^2\,\mathrm{tr}\,(\phi^\dagger\phi) - \frac{M_2^2}{2}\,\mathrm{tr}\,(\phi^\dagger\tilde{\phi} + h.c.) - M_3^2\sigma^\dagger\sigma \\
& - \left[\bar{Q}_L(Y_1\phi + Y_2\tilde{\phi})Q_R + \bar{\Psi}_L(Y_3\phi + Y_4\tilde{\phi})\Psi_R + h.c.\right] \\
& - \left[Y_5(\bar{\Psi}_L\chi_L S_R^c + \bar{\Psi}_R\chi_R S_L) + Y_6(S_L^T C S_L)\sigma + h.c.\right] \qquad (5)
\end{aligned}
$$

where the field $\tilde{\phi} \equiv \tau_2\phi^*\tau_2$ has the same quantum numbers as ϕ: $\tilde{\phi} \sim (2,\ 2,\ 0)$. By integrating out the auxiliary scalar fields one can reproduce the 4-f structures of eq. (3).

Consider now parity breaking in the present LR model. Using the Yukawa couplings of the doublets χ_L and χ_R, one can calculate the fermion-loop contributions to the quartic couplings $\lambda_1[(\chi_L^\dagger\chi_L)^2 + (\chi_R^\dagger\chi_R)^2]$ and $2\lambda_2(\chi_L^\dagger\chi_L)(\chi_R^\dagger\chi_R)$ in the effective Higgs potential. One can easily make sure that the fermion–loop diagrams yield $\lambda_1 = \lambda_2$. Recall that one needs $\lambda_2 > \lambda_1$ to have spontaneous parity breaking in the LR models. As we shall see, taking into account the gauge-boson loop contributions to λ_1 and λ_2 will automatically secure this relation.

Both λ_1 and λ_2 obtain corrections from $U(1)_{B-L}$ gauge boson loops, whereas only λ_1 is corrected by diagrams with W_L^i or W_R^i loops. Since all these contributions have a relative minus sign compared to the fermion loop ones, one finds $\lambda_2 > \lambda_1$ irrespective of the values of the Yukawa or gauge couplings or any other parameter of the model, provided that the $SU(2)$ gauge coupling $g_2 \neq 0$. Thus the condition for spontaneous parity breaking is automatically satisfied in our model.

We have a very interesting situation here. In a model with composite triplets Δ_L and Δ_R parity is never broken, i.e. the model is not phenomenologically viable. At the same time, in the model with two composite doublets χ_L and χ_R instead of two triplets (which requires introduction of an additional singlet fermion S_L) parity is broken automatically. This means that, unlike in the conventional LR models, in the composite Higgs approach *whether or not*

parity is spontaneously broken depends on the particle content of the model rather than on the choice of the parameters of the Higgs potential.

Although there are no triplet Higgs bosons in the present version of the model, a modified seesaw mechanism is operative which ensures the smallness of the masses of neutrinos taking part in the usual electroweak interactions. This is because the neutrinos mix with the gauge–singlet fermion S_L. Minimization of the effective Higgs potential shows that for the choice of the 4-f couplings resulting in the dynamical breaking of the LR gauge symmetry, the χ_L and σ fields do not develop VEVs; for this reason the lightest neutrinos remain massless in our model.

Analysis of the vacuum structure of the model shows that for the right–handed scale $v_R = \langle\chi_R^0\rangle$ to lie in the phenomenologically allowed domain, the effective (mass)^2 term of the composite bi-doublet ϕ must always be positive; the electroweak symmetry is broken because of the mixing of ϕ with χ_R. Thus we have a tumbling scenario where the breakdown of parity and $SU(2)_R$ occurring at the scale μ_R causes the electroweak symmetry breaking at a lower scale μ_{EW}.

The physical Higgs boson sector of the model includes 4 charged scalars, 4 neutral CP–even and 2 CP–odd scalars. Two of neutral CP–even bosons, H_1 and H_2, are directly related to the two steps of symmetry breaking, $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ and $SU(2)_L \times U(1)_Y \to U(1)_{em}$. In the bubble approximation the mass of H_2, whose properties are similar to the properties of the standard model Higgs boson, is approximately $2m_t$. This coincides with the top–condensate prediction[1)−4)] and reflects the fact that this scalar is the $t\bar{t}$ bound state. Analogously, H_1 is the bound state of heavy neutrinos with its mass being approximately twice the heavy neutrino mass $M \sim \mu_R$.

In conventional LR models only one scalar, which is the analog of the standard model Higgs boson, is light (at the electroweak scale), all the others have their masses of the order of the right–handed scale M. In our case, the masses of those scalars are also proportional to M, but all of them except the mass of H_1 have some suppression factors. The masses of χ_L are suppressed because of their pseudo–Goldstone nature. It was already mentioned that at the fermion–bubble level $\lambda_1 = \lambda_2$ which means that the (χ_L, χ_R) sector of the Higgs potential depends on χ_L and χ_R only through the combination $(\chi_L^\dagger\chi_L + \chi_R^\dagger\chi_R)$. This, in turn, implies that the Higgs potential has a global $SU(4)$ symmetry which is bigger than the original gauge symmetry. In fact, the origin of this $SU(4)$ symmetry can be traced back to the 4-f operators of eq. (3). It is an accidental symmetry resulting from the gauge invariance and parity symmetry of the G_7 term. Note that no such symmetry occurs in conventional LR models. After χ_R^0 acquires a VEV, $SU(4)$ symmetry is broken down to $SU(3)$, and the components of χ_L are the corresponding Goldstone bosons. The $SU(4)$ symmetry of the Higgs potential is not exact: it is broken by the $SU(2)$ gauge–boson loop contributions which make $\lambda_2 > \lambda_1$ (and also by ϕ–dependent terms). As a result, χ_L are pseudo–Goldstone bosons with their mass vanishing in the limit $g_2 \to 0$, $m_\tau \to 0$. In fact, though the $SU(2)$ gauge coupling constant g_2 is smaller than the typical Yukawa constants in our model, it is not too small; estimates of the χ_L mass give $M_{\chi_L} \sim 10^{-1}M$.

The bi-doublet ϕ can be viewed as consisting of two doublets, ϕ_1 which develops a VEV and

is similar to the standard model Higgs doublet, and the orthogonal field ϕ_2 which is VEVless. In the conventional LR models ϕ_2 is heavy, $M_{\phi_2} \sim M$. In our case the mass of its charged components $\phi_2^{\pm}$ is suppressed by the factor m_τ/m_t and is therefore of the order $10^{-2}M$. The masses of the neutral CP–even and CP–odd components are even smaller; they are related to the masses of $\phi_2^{\pm}$ and the standard model Higgs boson H_2 by

$$M^2_{\phi^0_{2r}} = M^2_{\phi^0_{2i}} = M^2_{\phi^{\pm}_2} - \frac{M^2_{H_2}}{2} = \frac{2}{3} M^2 \frac{m_\tau^2}{m_t^2} - \frac{M^2_{H_2}}{2}. \tag{6}$$

This equation imposes an upper limit on the standard model Higgs boson mass M_{H_2} (for a given M) or a lower limit on the right–handed mass M (for a given M_{H_2}). These limits follow from the requirement that $M^2_{\phi_2^{\pm}}$ be positive, i.e. from the vacuum stability condition. For example, for $M_{H_2} \approx 200$ GeV we find $M \gtrsim 17$ TeV.

Assuming that only one of the neutral components of the bi-doublet develops a non-vanishing VEV, one can readily relate the top quark mass to the scale of new physics Λ (on which it depends logarithmically) and the electroweak VEV. For example, for $\Lambda \simeq 10^{15}$ GeV, one finds $m_t \simeq 165$ GeV. However, this only holds in the bubble approximation; the renormalization group improved result is substantially higher, 220–230 GeV. In this respect the predictions of the model are similar to those of BHL[3]. If one assumes that both neutral components of the bi-doublet develop non-vanishing VEVs, one can easily get an acceptable value of m_t. However, the top quark mass is adjusted rather than predicted, i.e. one looses predictivity in the fermion sector in this case (although keeps interesting predictions in the Higgs boson sector).

To summarize, we have a successful dynamical LR model in which a tumbling symmetry breaking mechanism is operative. The model exhibits a number of low and intermediate scale Higgs bosons and predicts the relations between masses of various scalars and between fermion and Higgs boson masses which are in principle testable. If the right–handed scale μ_R is of the order of a few tens of TeV, the neutral CP–even and CP–odd scalars ϕ^0_{2r} and ϕ^0_{2i} can be even lighter than the electroweak Higgs boson. In fact, they can be as light as ~ 50 GeV and so might be observable at LEP2. Such light ϕ^0_{2r} and ϕ^0_{2i} can also provide a positive contribution to $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$ which is necessary to account for the discrepancy between the LEP observations and the standard model predictions.

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